The Space Propulsion Sizing Program

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ABSTRACT

The Space Propulsion Sizing Program is an advanced tool to facilitate vehicle design and broad system-level trade studies. It was designed to provide a simple and reliable means for rapid propulsion trade studies during the conceptual design phase. This is accomplished through a combination of mass estimating relationships, bottom-up calculations, and historical data to size several vehicle subsystems. Microsoft Excel and Visual BASIC were selected as the medium for the application of these methods. Through the versatility of Visual BASIC, several output modes are available for the vehicle mass breakdown and geometry estimates. The capability and reliability of this unique tool has been demonstrated by comparing estimates to real vehicles.

1.0 Introduction

The Space Propulsion Sizing Program (SPSP) was developed to fill a void in reliable in-space propulsion system conceptual design. There was a specific desire to be able to quickly and easily estimate propulsion stages to perform trade studies on mission scenarios and technology. SPSP was originally conceived as high-level conceptual design tool; the estimates generated from SPSP were to be considered first-order approximations of an actual solution. However, SPSP was evolved into satisfying more detailed designs. It is still an ideal tool for rapid trade studies; a single design point in a trade tree takes less than 30 minutes from start to finish. The capabilities extend to from high-level design to detailed conceptual design.

The approach of SPSP is the combination of the best mass estimating methods available. The combination of these methods with built-in functionality allows the user to progress through the design process from an initial concept to a vehicle with a detailed mass breakdown and geometry sizing. The additional capabilities from launch vehicle design to analysis of planetary landers provide the user with a wide range of possible design options and trade study variations.

2.0 Mass Estimating Design Approach

The primary approach for an accurate sizing tool was to combine the bottom-up calculations, mass estimating relationships (MERs), and historical data. The MERs were selected from several sources[1,2,3] to estimate the mass and dimensions of various components and were comprised of curve fits and surface fits to specific groups of historical data. The bottom-up calculations were based entirely on the fundamentals of the systems. The historical data was primarily used to validate component-level estimates and add realistic calculation corrections. Each module of the program was created with one or more of these mass-estimating methods in order to create the most reliable program possible. The combination of methods for each subsystem module is shown in Table 1.

Table 1. Sizing methods used for each subsystem module

MODULE \ METHOD	Database	Regression	Mass Est. Relationship	Bottom-Up Calculation	Method Averaging
Engine	X	X			
Main Tanks		X		X	X
Propellant Feed			X	X	
RCS	X	X		X	
Power				X	
Structures			X		
Avionics			X		

2.1. Main Engines

The user is able to select the number and type of engines to use in the vehicle. The user chooses the engine from a drop-down list that is connected to a large historical database. The main engine characteristics are determined from the comprehensive database, consisting of over 100 engines with nine propellant combinations, including cryogenic, storable, and nuclear. Most of the engines in the database were flight qualified and flown; the database includes engines that are still being produced and no longer produced.

The main engine module offers the additional flexibility of a user-defined engine. With this option, the user defines the amount of thrust and the propellant combination; the characteristics are determined using several curve-fit regressions. If a maximum acceleration limit is imposed on the vehicle, the user-defined engine can be automatically sized to this limit by adjusting the engine thrust.

This approach offers complete accuracy in mass and sizing estimates for engines selected from the database because the values used are for known engines. For user-defined engines, the accuracy is limited by the regression associated with the selected propellant combination. The average error is approximately 5% for dimensions and less than 10% for mass. However, these errors, which seem large, equate to about 0.25 m and 30 kg, respectively. This small magnitude of the actual error is acceptable for the high-level designs the program is meant to satisfy.

2.2. Main Tanks

The primary approach for the main tank module is achieved through the fundamental calculation of the pressure vessel stress[4]. For a given operating pressure, factor of safety, and pressure vessel skin material, the required minimum thickness is calculated. All tanks are initially sized as spheres. If the diameter exceeds the user-defined envelope, the tanks are re-sized as cylinders with either hemispherical or elliptical ends; this shape is known as a pill tank. The user controls the shape of the ends. The exceptions are nested and toroidal tanks. For nested tanks, the upper tank diameter is sized as usual and is applied to the lower tank. In case the lower tank becomes too flat, the sizing routine allows the lower tank to become completed embedded within the upper tank or to become a pill with one end nested inside the upper tank. For toroidal shaped tanks, the tank is assumed to have a circular cross-section, and the shape is adjusted to a pill cross-section if a larger volume is needed. The inner radii of the fuel and oxidizer tanks can either be independent or constrained to the same size. For any of the configurations, the pressure vessel skin mass is found as the product of the material density, tank wall thickness, and tank surface area. The insulation mass is found as the product of the insulation material density, insulation thickness, and exposed tank surface area. The insulation thickness is user-defined.

An effort was made to validate this approach. However, whenever this method was used to estimate tanks actually flown for space applications, the process was consistently 25% to 35% low on the mass estimates. The error was attributed to a lack of consideration for propellant management devices, tank fittings, attachments, and additional structural supports. To account for these other components, an adjustment algorithm was created. The same tanks used to test the bottom-up calculation were estimated using several MERs for propellant tank mass estimating. For each of the MERs and for the bottom-up method, regressions were independently generated to adjust each tank mass estimate. Adjusting the MERs and bottom-up calculation with the regressions and averaging the adjusted masses created the final algorithm.

This complicated procedure provides a more accurate tank mass-estimating scheme than any of the MERs or bottom-up calculation could provide separately. The errors are on the order of 1-2% for large tanks and about 3-4% for smaller tanks.

2.3. Propellant Feed System

The mass calculations for the propellant feed system are based entirely on MERs that determine feed system and pressurant system masses[1]. The user inputs the number of feed lines and selects the type of oxidizer and fuel pressurization systems. Based on these selections, tank operating pressures, and tank volumes the pressurant mass and pressurization system dry mass are calculated. The pressurant tank dimensions are calculated from the required amount of pressurant, using a bottom-up calculation. Since the bottom-up calculations are only being used to determine the physical dimensions, the adjusting and averaging algorithm created for the main tank module is not necessary.

2.4. Reaction Control System

The Reaction Control System (RCS) is primarily based on the user's selection of a particular small thruster, required maneuvering velocity change, number of thrusters, and number of propellant and pressurant tanks. The thrusters are selected from a database of about 50 small thrusters that were used for space applications; this database contains detailed characteristics of each thruster. The rocket equation is used to calculate the required amount of propellant, which leads to sizing the propellant tanks. The tanks are approximated using the bottom-up calculation method applied to the main tank module. This approach offers a simple bottom-up estimate of an RCS that is independent of the main vehicle propulsion system.

The RCS module has the additional capability to use a feed-off of the main propulsion system.

This method applies the same propellant combination to the RCS to eliminate additional tanks. This uses the same process as an independent RCS, but the user is required to choose a thrust level, which dictates the thruster mass. The relationship between thruster mass and thrust-level was created using a regression through the comprehensive database.

2.5. Power System

The power system calculations are entirely based on the fundamentals of power generation. The primary and secondary system masses are found using the methods described by Brown[5]. The main drivers of the calculation are the average required power, nominal voltage, power margin, generation method, and mission duration. The calculations are limited because the result only includes the masses of the power generation system and does not include the power transmission or wiring masses. The avionics system module incorporates the wiring mass.

2.6. Structures

The structural masses are found using Emory Lynn's MERs (Ref. 1), which are based on regressions through historical data points. The dimensions for the structural elements are found using relations to other components of the vehicle such as the main tanks or main engines. The material type and dimensions are applied to the MERs, resulting in the mass estimates for each of the structural elements. These estimates for very large or very small vehicles are too large or too small, respectively. This is due to the range of data originally used to create the MERs; however, the MERs are currently the only means employed.

2.7. Avionics System

The avionics system masses are also found using the MERs developed by Emory Lynn (Ref. 1). The user decides if the vehicle is crewed, reusable, performs docking maneuvers, or a combination of the three. From the selections, certain components are added to the inventory of the avionics system; however, the MERs rely on historical data, which used older, heavier technology. Additionally, the only component that is dependent on vehicle parameters is the wiring mass, which is based on the overall length of the vehicle. This causes the avionics system to be over-sized for a modern vehicle.

3.0 Geometry Estimating and Output Formats

The geometry estimates for the vehicle are based on the more significant subsystems. The length found by stacking the various structural elements, main tanks, and engine to approximate the overall length of the vehicle; the main propellant tank with the largest diameter governs the diameter of the vehicle. The dimensions of other subsystems are considered for the more advanced output formats. The simplest output is in a 2-dimensional cross-section of the vehicle drawn using the built-in Excel line plot. Computer aided design (CAD) software packages provide much more detail and accuracy as to the specific dimensions of the vehicle. Using the Visual BASIC language, the geometry data is easily outputted to any compatible CAD software. The CAD software that is specifically imbedded into SPSP is Pro-Engineer due to the simplicity of integrating the data output for Pro-Engineer. Pro-Engineer offers additional design analysis tools that are easily applied to designs made with SPSP. Other software packages can also be integrated in this manner. Such integration has been demonstrated with IDEAS and MATLAB, though these are not currently programmed into SPSP and must be added separately.

Figure 1 shows the Excel 2-dimensional line plot of a vehicle, and Figure 2 shows the Pro-Engineer 3-dimensional view of the same vehicle. The comparison highlights the Excel plot limitations; the 2-dimensional image shows the vehicle as about 17 m tall. However, the more accurate Pro-Engineer model shows the vehicle to be 17.59 m tall. The error is due to advanced part mating capability in the CAD software; the thrust structure should be tangent to the bottom tank. Pro-Engineer can apply that logic, but the Excel plot does not have such capability.

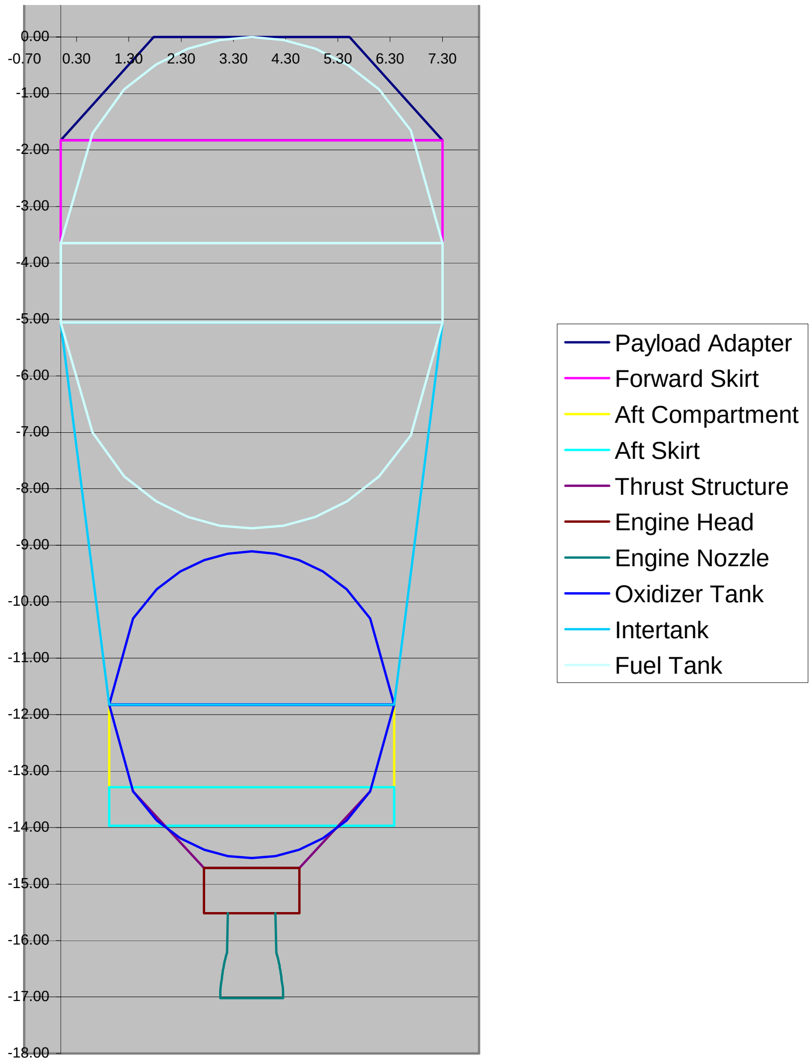

Figure 1. Excel 2-dimensional line plot.

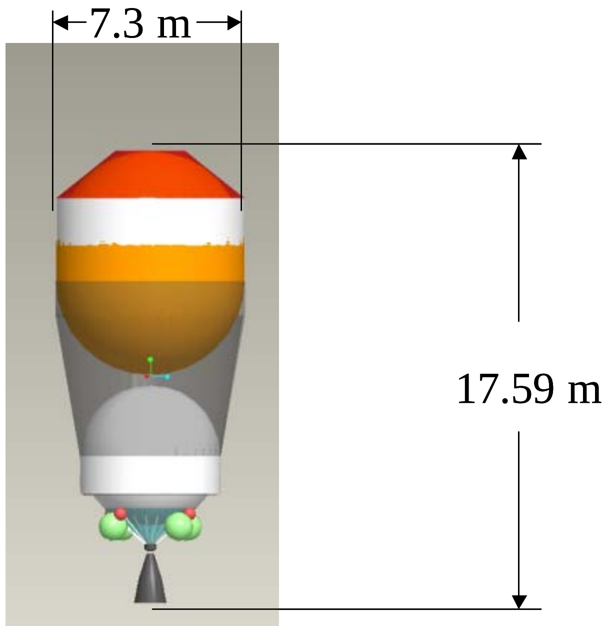

Figure 2. Pro-Engineer 3-dimensional output.

4.0 Spin-off Tools and Additional Capabilities

As SPSP was used for more trade studies and design objectives, additional requirements were imposed on the program. Many of the requirements lead to the development of other tools that are exclusively used in conjunction with SPSP. Some additional capabilities were added as spin-off tools that satisfy specific needs; whereas, other added capabilities were folded into SPSP directly. The additions were relatively easy to include due to one of the significant design features of SPSP: a simple interface with easily adaptable modules. The added tools include a stage optimization program, lander design tool, in-space tanker/depot tool, and a launch vehicle design and analysis tool. These tools and built-in SPSP functionality are explained in more detail.

4.1. Staging Tool with Optimizer

In order to facilitate the design of multistage vehicles, the staging tool is used with SPSP. After a user designs the first stage of a multistage vehicle in SPSP, the staging tool is opened and automatically creates multiple versions of the first stage. Te tool allows up to five stages; each stage is associated with a separate SPSP file, allowing complete independence of each stage. Within the staging tool are two optimization routines. The first optimizer allows the user to minimize the gross mass of the multistage vehicle; this assumes that the vehicles can be different size stages. The second optimizer allows the user to optimize the velocity change maneuvers among the several stages by specifying that each of the stages is identical in size. The staging tool can also be combined with other SPSP spin-off tools.

4.2. Tanker Sizing Tool

The tanker-sizing tool is used to design in-space tankers. Such vehicles have been designed in support of propellant transfer and propellant aggregation studies. The tanker tool only differs from the main SPSP tool by the lack of a main engine. The assumption governing the tanker designs is that a tanker would require some other element for maneuvering. The user is able to design the tanker for any amount of propellant and any propellant combination; the user may also choose to size the tanker for only one propellant, either an oxidizer or a fuel. Since there is not fundamental difference between tanker vehicles and propellant depots, the tanker-sizing tool is applicable to depot design. This similarity is particularly useful for propellant aggregation studies requiring both types of vehicles.

4.3. Lander Sizing Tool

The main SPSP tool was modified to include additional hardware necessary for a landing vehicle; this was the step taken to create the lander-sizing tool. Based on the landing structure for the Apollo lunar excursion module, additional structural mass necessary for landing was calculated as 3% of the touchdown mass[2]. With this addition, SPSP is able to size un-crewed landing vehicles. In order to size crewed landers, a habitat mass must be generated through some other means since SPSP does not contain habitable element sizing capability.

4.4. Launch Vehicle Design and Analysis Tool

Since the primary difference between launch vehicle stages and in-space stages is negligible on the conceptual level, the launch vehicle design and analysis tool was created using the staging tool and a fourth-order Runge-Kutta integration scheme. A user can create a multistage vehicle in the staging tool; then, the pertinent data of the vehicle is outputted to the MATLAB program, which contains the routine to integrate the equations of motion. The routine targets the launch trajectory to achieve the orbital perigee and apogee altitudes by changing the initial pitch angle; the payload can either be specified or optimized. The trajectory can be further analyzed to determine the relationship between payload capability and the insertion orbit. This analysis is useful for determining the increased payload capability for a lower insertion orbit, or vice-versa.

4.5. Additional Capabilities

For the more complicated maneuver sequences, a multiple payload with multiple maneuvers calculator was added. This calculator is useful when designing a vehicle that must perform several dissimilar maneuvers and varying payload amounts. Prior to the addition of this calculator, SPSP was only able to size a vehicle for one payload through one maneuver.

Many of the propellant combinations used by SPSP include a cryogens; such propellants boil-off in space. Since the amount of propellant lost to boil-off can be significant, the capability to determine the losses have been added to SPSP as an automatic built-in calculation. The calculations consider the amount of multilayer insulation, size of the propellant tank, and the cryogen storage temperature. Additionally, the amount calculated is also applied as a maximum amount that zero boil-off hardware should weigh to make a positive impact on the propellant storage system.

5.0 Benchmarking

The advantage of any tool is the user's ability to design or analyze a new system; however, the results are not always reliable and grounded in reality. To validate SPSP, the S-IVB, Atlas-Centaur III, and Delta IV upper stages were modeled. Since the upper stage of a launch vehicle performs most of its engine firing in space, these stages represent the type of vehicle SPSP was designed to model. Also, the launch vehicle analysis tool was validated against conceptual launch vehicles designed as part of the Exploration Systems Architecture Study (ESAS).

Figure 3 shows a graphical comparison of the actual and SPSP-generated estimate of the S-IVB upper stage at burnout. The graph is of the percentage that each subsystem comprises of the burnout mass. The primary difference is the conservative estimate for residual propellant masses, which is the amount of unusable propellant left in the tanks and feed-lines. The mass estimate at burnout is less than a quarter percent above the actual burnout mass. The burnout mass is used in this example since the only difference between burnout mass and gross mass is the amount of propellant.

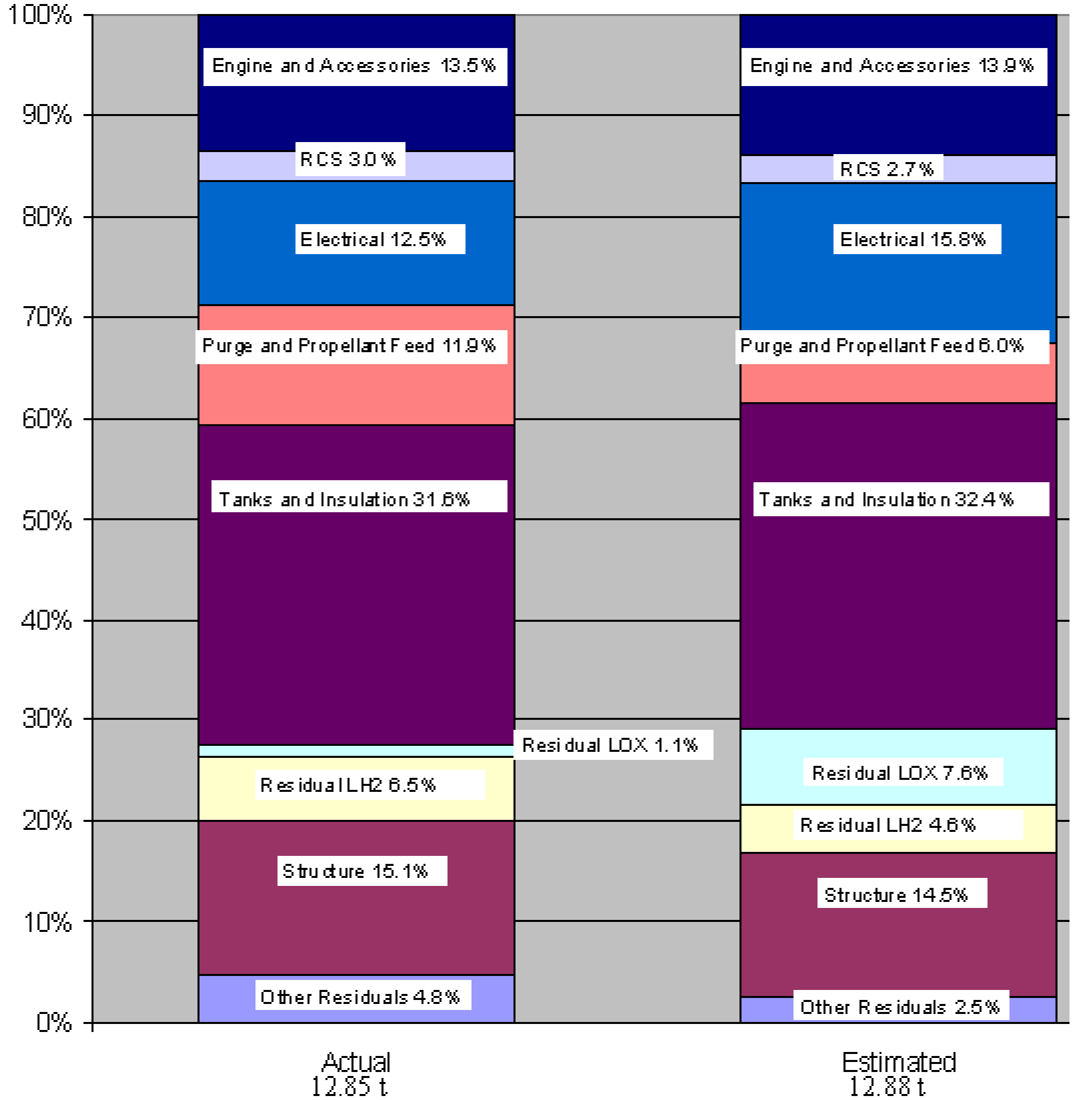

Figure 3. Subsystem breakdown of actual and modeled S-IVB.

The comparisons for the SPSP model of Atlas-Centaur III and Delta IV upper stages are shown in table 2. The small errors, less than 3%, demonstrate that SPSP can model vehicles with an acceptable level of realism. The error is likely due to the basis of the avionics system estimate on old technology. The Delta IV upper stage is also used to validate the geometry modeling in SPSP; this is due to a lack of available geometry details of the other vehicles. The geometry output comparison is shown in figure 4.

Table 2. Comparisons of actual and SPSP models for Atlas-Centaur III and Delta IV upper stages.

	Actual Value	SPSP Estimate	% Error
Atlas-Centaur III			
Gross Mass (kg)	18960	19322	1.91%
Inert Mass (kg)	2180	2193	0.59%
Propellant Mass (kg)	16780	16972	1.14%
Prop. Mass Fraction	0.885	0.878	-0.75%
Delta IV			
Gross Mass (kg)	30710	30564	-1.63%
Inert Mass (kg)	3490	3507	0.49%
Propellant Mass (kg)	27200	26756	-0.48%
Prop. Mass Fraction	0.89	0.875	-1.67%

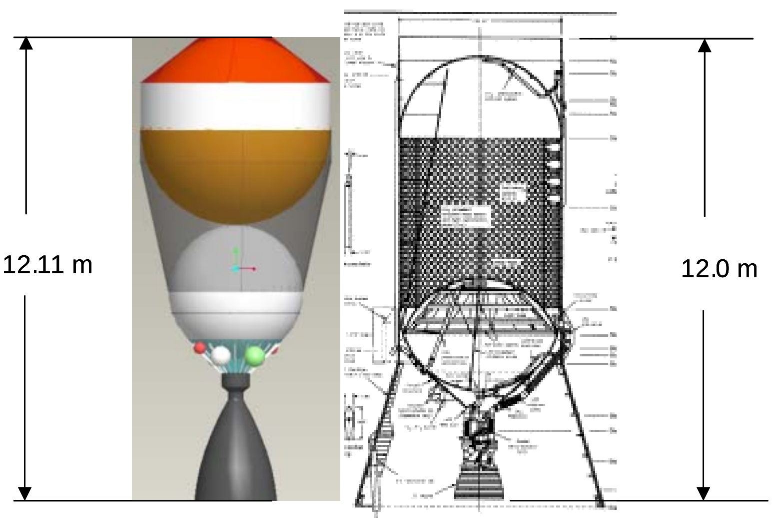

Figure 4. Comparison of actual and SPSP geometry models for Delta IV upper stage.

The successful benchmarking of the primary SPSP tool increases the user's reliance in the tool. Since the SPSP tool mass estimating capabilities are trustworthy, it is naturally assumed that the extensions of the tool into tanker sizing and lander sizing are similarly reliable.

The launch vehicle tool certification was accomplished by targeting the same payload mass to nearly the same insertion orbit as vehicles designed through other means. The launch vehicle trajectories were originally created using the Program to Optimize Simulated Trajectories (POST) at the NASA Marshall Space Flight Center. The SPSP launch vehicle trajectories were matched against the POST trajectories for several different launch vehicles. The apogee and perigee altitudes were within a few kilometers of the target values. This exercise primarily demonstrated the accuracy of the initial conditions targeting routine to achieve the proper orbit and the equations of motion integration technique.

The targeting errors are associated with the inherent limitations of the integration technique and the lack of payload shroud jettison during launch. The limitations of the integrator are almost negligible; however, the payload shroud during most launches is jettisoned near the end of the launch sequence after exiting the atmosphere and before orbit insertion. Despite these errors, the trajectory calculator is sufficiently accurate to rely on it as a fast means of analyzing launch vehicle performance.

6.0 Summary

The simple interface, multiple output capabilities, and adaptability to new requirements make SPSP a necessary component of a vehicle designer's toolbox. The main SPSP and spin-off tools are robust and reliable for the high-level conceptual design and rapid trade study niche that they are meant to satisfy. All of the advantages of the software package allow the user to focus on design and trade studies from launch to in-space propulsion to landing on a distant planet or moon to returning to Earth orbit.

7.0 References

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